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# Gas-driven filter pressing in magmas: Insights into in situ melt segregation from crystal mushes

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## ABSTRACT

Gas-driven filter pressing is the process of melt expulsion from a volatile-saturated crystal mush, induced by the buildup and subsequent release of gas pressure. Filter pressing is inferred to play a major role in magma fractionation at shallow depths (< 10 km) by moving melt and gas relative to the solid, crystalline framework. However, the magmatic conditions at which this process operates remain poorly constrained. We present novel experimental data that illustrate how the crystal content of the mush affects the ability of gas-driven filter pressing. Hydrous haplogranitic (2.1 wt.% water in the melt) and dacitic (4.2 wt.% water in the melt) crystal mushes, exhibiting a wide range of crystallinity (34-80 vol.%), were investigated by in situ, high temperature (500-800 °C) synchrotron X-ray tomographic microscopy with high spatial (3  $\mu\text{m}/\text{pixel}$ ) and temporal resolution (8 sec. per 3D dataset). Our experimental results show that gas-driven filter pressing operates only below the maximum packing of bubbles and crystals (~74 vol.%). Above this threshold, the mush tends to fracture. Therefore, the efficiency of gas-driven filter pressing is promoted close to the percolation threshold and when the mush inflates slowly relative to build-up of pressure and expulsion of melt. Such observations offer a likely explanation for the production of eruptible, crystal-poor magmas within the Earth's crust.

## INTRODUCTION

Magmatic differentiation involves the physical separation of crystals from their viscous coexisting melts. ~~The re~~In shallow magma reservoirs relatively slow, ~~yet~~ ~~poorly constrained,~~ processes of compaction ~~processes (at~~ high crystallinities ~~( $\geq$  70~~ vol.% crystals; Jackson et al, 2003), and hindered settling ~~at~~ (intermediate crystallinities ~~( $\geq$  40-50~~ vol.% crystals; Bachmann and Bergantz, 2004) that drive this separation in shallow magma reservoirs, can be enhanced by the concentration of volatiles in the melt phase and their subsequent exsolution (Sisson and Bacon, 1999).

Volatile exsolution at low solidification pressures causes the magma to expand, while the high viscosity of the crystallising magma ( $> 10^5$  Pa·s) impedes the bulk inflation of the system. In this scenario, gradients in crystallinity, vesiculation and pressure therefore drive the melt towards regions of lower crystallinity and pressure. SiO<sub>2</sub>-rich melts are saturated with 6-8 wt.% H<sub>2</sub>O at the depths of  $< 10$  km (Hui et al., 2009) typical of most silicic magma reservoirs, suggesting that this process may be ubiquitous. This gas-driven filter pressing mechanisms may drive segregation of compositionally-variable, crystal-poor melts typically forming heterogeneous large ignimbrite deposits (Lipman et al., 1966). The goal of the present study is to quantify the influence of the crystal fraction ( $\phi$ ) on melt permeability in order to define the magmatic conditions where gas-driven filter pressing is an efficient mechanism for melt extraction and generation of eruptible, crystal-poor silicic magmas.

## METHODS

To capture simulated gas-driven filter pressing, high temperature ( $T = 500$ - $800$  °C) experiments were conducted on a suite of pre-synthesised highly differentiated, volatile- and crystal-poor melts (haplogranites, H5; 2.1 wt.% H<sub>2</sub>O in the glass,  $\phi = 0.34, 0.47$  corundum crystals) and less evolved, volatile- and crystal-rich melts (dacites, F; 4.2 wt.% H<sub>2</sub>O in the glass,  $\phi = 0.5, 0.6, 0.7, 0.8$  quartz crystals); using the high spatial ( $3 \mu\text{m}/\text{pixel}$ ) and temporal resolution ( $\sim 8$  sec. per single for each 3D dataset) of synchrotron X-ray tomographic microscopy at the TOMCAT beamline, (Swiss Light Source), coupled to a laser-based heating system (Fife et al. 2012). Crystal-free samples of both compositions were also used as benchmark during experiments.

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Comment [A1]: Technically anything with more than 0.2 is not crystal poor...

The starting materials have bubble volume fractions ( $\beta$ )  $\leq 0.01$  and some heterogeneity in the crystal distribution (mean size of 68  $\mu\text{m}$ ); however, neither crystallisation nor melting of crystals occurred during heating (i.e.  $\phi$  was constant throughout). ~~We do not simulate Crystallisation~~crystallisation-driven gas exsolution ~~per se was not simulated in our tests; rather~~ the different  $\phi$  bracketed the crystallinities occurring in natural gas-saturated mushes. The limited attenuation contrast between crystals and melt was maximised by edge-enhancement and post-acquisition phase retrieval. Technical details are reported in the Data Repository.

The haplogranites and dacites have the same initial melt viscosity ( $\eta_{\text{melt}} < 1.3$  Pa·s). Preferential bubble nucleation on the crystal phases is not expected in either system, as SiO<sub>2</sub>-rich melts are the wetting phase (Laporte, 1994, Hurwitz and Navon, 1994). Although both systems should not crystallise during the experiments, ~~c~~Chemical differences between the samples (e.g. SiO<sub>2</sub> content, initial H<sub>2</sub>O content) ~~could may~~ affect the physical behaviour of bubble nucleation and growth during  $T$  increase to 800 °C. ~~but w~~We do not assume both systems should have the same physico-chemical behaviour: rather we test which allows gas-driven filter pressing.

Sequential 3D images provided a 4D (3D + time) record of bubble growth and microstructure evolution for each  $T$  and  $\phi$  as the samples were heated step-wise (25 °C steps with a heating rate of 2 °C/s) between ~~500-475 °C (below the glass transition)~~ and 800 °C. ~~Heating steps were initiated at 475 °C (below the glass transition); isothermal, and~~ conditions were maintained for 3.5 minutes ~~before heating at each temperature to the next T.~~ Real-time visual inspection showed negligible bubble growth by the end of each  $T$  step. ~~S, but~~ samples did not achieve ~~perfect~~ textural equilibrium ~~conditions of vesiculation at a given each T; however~~However, gas-

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driven filter pressing is a process driven by rapid crystallisation and vesiculation (Sisson and Bacon, 1999), and therefore operate during textural and thermal dis~~which do not necessarily require equilibrium conditions to occur.~~

Karl-Fischer Titration (KFT; Behrens et al., 1996) ~~method~~ was used to quantify H<sub>2</sub>O outgassing ~~from the dacites~~ over the same *T*-time path for samples of the same volume to those used in the X-ray tomographic microscopy experiments.

#### 4D MICROSTRUCTURAL EVOLUTION

Time-integrated textural analysis reveals that gas bubbles nucleate and undergo diffusion-limited grow (~~diffusion-limited growth~~; Data Repository) homogeneously throughout crystal-free haplogranites and dacites, ~~but are found predominantly in melt-rich regions within the crystal-bearing samples.~~ Fractures are only generated during vesiculation. No formation or healing of fractures is observed during cooling after experiments.

~~At the spatial resolution of our experiments no heterogeneous bubble nucleation is observed. It is expected that a film of melt is always present between bubbles and crystals, since SiO<sub>2</sub>-rich melts are a wetting phase (Laporte, 1994), and corundum and quartz crystals are inefficient sites for bubble nucleation (Hurwitz and Navon, 1994). Fractures are generated during vesiculation, and no formation or healing of fractures is observed during cooling after experiments.~~

In the haplogranitic samples there is no evidence for gas-driven filter pressing. Bubbles increase their volume with minimal coalescence, and form a polygonal network (Figures 1A-D) similar to that found in natural felsic frothy pumices. Despite significant initial intercrystalline porosity, bubble growth in the crystal bearing samples preferentially occurs in melt-rich regions, ~~Within the crystal rich regions bubble distribution is homogenous. Bubble growth~~ sharply ~~reducing~~ the volume of

the interstitial melt (local  $\beta = 0.9$ ), and generating peripheral compacted crystal clusters (Figures 1A-D). At  $T \geq 550$  °C major conchoidal fractures develop (Figures 1C-D, arrows), with smaller fractures up to 200  $\mu\text{m}$  length connecting inflated gas-rich regions (Figure 1D). Fractures are arranged at high angles ( $70^\circ$  to  $90^\circ$ ) relative to the vertical sample axis along which sample expansion occurs. The fractures radiate out from the inflating gas-rich, crystal-poor regions, passing through both crystals and residual melt (Figures 1C-D, arrows).

In contrast, the dacitic samples show gas-driven filter pressing. The individual bubbles are generally much larger than those ~~generated~~ in the haplogranitic samples (Figures 1E-H). At all temperatures -at  $\phi \leq 0.5$ ,- bubbles form and grow by extensive coalescence, ~~(predominantly through melt-film attenuation)~~ and no fracture is observed-between-expanding-bubbles,- At  $\phi = 0.6-0.7$ , bubbles deform around crystals during growth (Figure 1H), and melt concentrates into narrow (20-80  $\mu\text{m}$ -wide) channels within the crystal framework due to the pressure exerted by gas bubbles (Figure 1H, grey arrows from stretched bubbles). At  $T \geq 675$  °C, curved fractures form between large bubbles in the melt phase, and jagged fractures are found in the crystal-rich regions (Figure 1H, white arrows). At  $\phi = 0.8$ , no significant bubble nucleation and growth was observed at any temperature (see insets in Figure 2).

From these behaviours we ~~Here we~~ define a-the “ductile regime”; -when the sample undergoes inflation during vesiculation, and a-the “brittle regime”; when the sample fractures during vesiculation (with or without inflation). The mechanical evolution ~~of both regimes during vesiculation~~ can be described as a function of  $\phi$  and  $\beta$ . At  $\phi = 0.5-0.7$  (the target crystallinities of this study), with the ductile to brittle

transition ~~clearly~~ occurring at a residual melt fraction ( $\mu = 1 - \phi - \beta$ ) of about 0.25 (Figure 2).

#### **GAS EXTRACTION EFFICIENCY ~~AND MELT VISCOSITY~~**

~~The KFT analysis performed on the dacite samples that showed gas-driven filter pressing, supports the microstructural observations. In this system, The H<sub>2</sub>O exsolution, and therefore  $\eta_{melt}$  in all samples should be the same is constant for a given at each temperature. Comparison of the extraction profiles and bubble and expansion rates profiles therefore reveal s how differences in bulk viscosity and microstructure effect evolving permeability and the filter pressing process. The In the crystal free sample, exsolution of isolate bubbles degasses the melt before the formation of a permeable network (-shows a rapid increase in bubble volume (25% vol.%) from 575 °C followed shortly (at about 15 vol.%) by the rapid release of the majority of H<sub>2</sub>O at 600°C (Figure 3A) in the dacitic samples, suggesting a. as bubble volume increase allows interaction and the formation of a permeable network. At After network formation the temperature of network formation (625-650°C) gas exsolution is nearly complete, and bubble volume increases become appear to be thermally controlled.~~

~~accelerated H<sub>2</sub>O extraction at higher  $T$  and with decreasing  $\phi$  (Figure 3A). H<sub>2</sub>O extraction begins between 500 °C (high  $\phi$ ) and 625 °C (low  $\phi$ ) (Figure 3A). The crystal bearing samples show more variable behaviour. At  $\phi = 0.5$ , a first phase of bubble growth results in the formation of a permeable network and gas release. After a short two pulses of bubble growth (or ~20 vol.%) are observed at 575 °C and 625 °C between which period of no growth, a second phase of bubble expansion occurs, but accompanied by constant -The early growth is accompanied by extraction of~~

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~~~1wt.% H<sub>2</sub>O, implying a period of coalescence and permeability development.~~  
~~Throughout the hiatus in growth, the second volume expansion and a second hiatus~~  
~~(650 °C and 675–725 °C), gas extraction at a is lower than seen in the first release,~~  
~~and the rate; increases gradually with temperature. This suggests that no highly~~  
~~efficient pathway is accessible, and the extraction is diffusion controlled until .Above~~  
~~725 °C, increases in extraction rate occur as fracture is initiated and propagates.~~  
~~(tapping unconnected over-pressured pores).~~

At higher  $\phi$ , ~~(0.6, 0.7)~~ falling total extraction efficiency highlights the effect  
of crystals in reducing the ability of the sample to outgas. The ~~begins to fall.~~  $\phi = 0.6$   
sample shows near constant bubble growth (40 vol.%) for the majority of the heating  
schedule, whereas ~~from 575–675 °C, which spans spanning out-gassing only occurs~~  
~~at the the only period of measureable extraction (~1 vol.%) at 625 °C and the onset of~~  
~~brittle behaviour. While the~~ The total bubble tomography data show volume  
expansion is efficient, close to that predicted for the melt volume, supporting the  
microstructural observation that fracture is a minor component of the permeable  
network and brittle failure is localised with continued bubble growth elsewhere in the  
sample. The KFT data suggest that the majority of the remaining exsolved gas (~65%)  
remains trapped in unconnected porosity. The total bubble volume expansion is close  
to that predicted for the melt volume, supporting the microstructural observation that  
fracture is a minor component of the permeable network and brittle failure is localised  
with continued bubble growth elsewhere in the sample. The At  $\phi = 0.7$  overall  
extraction efficiency remains similar, but sample shows a significant reduction in  
overall bubble volume growth is now reduced (~20% of that possible in the crystal  
free sample), and pore over-pressures in the unconnected pores will be higher despite

193 ~~having a similar extraction profile and overall extraction efficiency and the onset of~~  
194 ~~brittle behaviour at a lower temperature. Assuming a similar distribution to that~~  
195 ~~observed in the tomography data, the limited porosity will have significant over~~  
196 ~~pressure after failure.~~ For  $\phi = 0.8$ , entirely in the brittle regime, ~~the an absence of~~  
197 ~~lack of both bubble growth-growth and gas extraction implies significant pore~~  
198 ~~overpressure with volume expansion prevented by the bulk viscosity of the sample. At~~  
199  $\phi = 0.8$ , no  $\text{H}_2\text{O}$  extraction is detected across the entire  $T$  range (Figure 3A), meaning  
200 ~~that the exsolved  $\text{H}_2\text{O}$  must remain trapped in a non-permeable bubble network,~~  
201 ~~and/or be released as low volume “silent” emission. At high  $\phi$ , low permeability is~~  
202 ~~maintained, whereas bubble coalescence allows gas loss at  $\phi \leq 0.5$ .~~

203 At  $\phi = 0.6-0.7$ ,  $\text{H}_2\text{O}$  extraction occurs across a restricted  $T$  range ( $\leq 75^\circ\text{C}$ ),  
204 and after the onset of brittle behaviour  $\text{H}_2\text{O}$  extraction is below the limit of detection  
205 ( $\sim 0.02$  wt.%) at all temperatures. The onset of brittle behaviour is accompanied by an  
206 increase in the KFT uncertainty, which suggests that fracture enhanced permeability is  
207 permitting continuous low volume “silent” emission of gas (see Data Repository). At  
208  $\phi = 0.8$ , no  $\text{H}_2\text{O}$  extraction is detected across the entire  $T$  range (Figure 3A), meaning  
209 ~~that the exsolved  $\text{H}_2\text{O}$  must remain trapped in a non-permeable bubble network,~~  
210 ~~and/or be released as low volume “silent” emission. These two processes may be~~  
211 ~~operating simultaneously.~~

## 212 DISCUSSION AND CONCLUSIONS

213 Our *in situ* X-ray tomographic microscopy data reveal that gas driven filter  
214 pressing operates only when bulk sample expansion occurs without fracturing or the  
215 development of gas permeable pore networks. The gas-driven filter pressing process  
216 appears to be most efficient in crystal mushes ( $0.5 \leq \phi \leq 0.7$ ), a minimum of  $\sim 3$  wt.%

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H<sub>2</sub>O (Figure 3B), and ~~over a limited window of crystallinity ( $0.6 \leq \phi \leq 0.7$ ) and~~ when  
bulk sample expansion occurs without fracturing or the development of gas permeable  
networks. In addition it appear to require  $\mu > 0.25$  (Figure 2), ~~i.e.~~ close to the  
percolation threshold ( $\mu = 0.22$ - $0.29$ ) or maximum packing fraction ( $\phi_{max} = 0.66$ - $0.74$   
for monodispersed suspensions) (Saar and Manga, 2002). The haplogranitic (2.1  
wt.%) sample achieve brittle failure at  $\phi \leq 0.47$  without substantial gas-driven filter  
pressing.

During these experiments  
Gas exsolution appears to begin shortly after  $T_g$ , with the initiation of  
permeable networks

~~At  $s$  When  $\phi \leq 0.5$ , permeability via bubble coalescence prevents gas-driven~~  
~~filter pressing. At  $\phi = 0.6$ - $0.7$  we see bubble growth driving filter pressing, until  $\mu$  is~~  
~~driven below the percolation threshold and exsolution only drives pore pressure~~  
~~increase until brittle failure occurs. A wide range of igneous rocks reveals~~  
~~achievement of the critical packing density of bubbles + crystals ( $\phi_{max} \sim 0.65$ - $0.75$  in~~  
~~basalts; Marsh, 1981;  $\mu \sim 0.3$  in granites; Wickham, 1987), which provides the last~~  
~~“snapshot” of a jammed system below the minimum volumetric proportion of melt to~~  
~~enable flow.~~

$\eta_{melt/bulk}$  is controlled by evolves as a function of  $T$ , and the residual dissolved H<sub>2</sub>O,  
bubble volume fraction and crystal volume fraction (Giordano et al., 2008), and will  
strongly control the effectiveness of gas-driven filter pressing. The bulk viscosity of  
the sample will also depend on the local crystal and bubble volume fractions (Pistone  
et al., 2012). As H<sub>2</sub>O exsolves from the melt,  $\eta_{melt}$  increases slowly at while H<sub>2</sub>O

**Comment [A2]:** Are we certain we are not seeing it at 0.5 as well. Trapped bubbles mean some pore pressure, and therefore I would suspect the processes is occurring, just maybe not as efficiently as in the 0.6 sample where the instantaneous increase in trapped gas at ~ 1% extraction causes failure? Is it just much slower at 0.5?

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remains contents > 2 wt.%, and more rapidly but more rapidly at H<sub>2</sub>O contents at < 2 wt.% (Giordano et al., 2008), and can be estimated using the KFT and tomography data (Pistone et al., 2012) (Figure 3B), up the point of (Giordano et al., 2008). Where bubbles coalescence is the dominant mechanism ( $\phi \leq 0.5$ ), the increase of  $\eta_{melt}$  due to H<sub>2</sub>O loss is more important than its decrease due to higher  $T$  (Figure 3B). Indeed,  $\eta_{melt}$  increases more distinctly when the residual H<sub>2</sub>O dissolved in the melt is < 2 wt.%. The same  $\eta_{melt}$  is expected to occur at  $\phi \geq 0.6$ ; however, the bulk H<sub>2</sub>O (i.e. dissolved H<sub>2</sub>O in the melt + exsolved gas bubbles) in the system remains in excess of 2 wt.% due to the incapacity of the system to outgas in presence of a continuous crystal network. After the brittle onset failure when the  $\gamma$ -samples enter into the Mohr-Coulomb regime where  $\eta_{melt}$  is meaningless (Figure 3B). The equation: Due to their initial low H<sub>2</sub>O content in the melt (2.1 wt.%), the haplogranitic systems reach failure even at  $\phi \leq 0.47$  without experiencing substantial gas driven filter pressing, although it may be possible that with slower heating rates gas driven filter pressing can be achieved. Conversely, the H<sub>2</sub>O rich (4.2 wt.%) dacitic systems have  $\eta_{melt}$  that allows gas driven filter pressing. This suggests that, at equivalent rates of volatile exsolution (i.e. relatively fast  $T-t$  paths simulating rapid crystallisation and vesiculation in natural systems) as simulated in our experiments, gas driven filter pressing might only be effective if the residual melt achieves a sufficiently low  $\eta_{melt}$  to prevent fracturing of the mush during gas exsolution, but nonetheless maintains a sufficiently high  $\eta_{melt}$  to allow for gas pressure build up and to expel melt from the crystal framework. Based on our results, the minimum H<sub>2</sub>O content in the silicic melt that allows gas driven filter pressing to be effective in crystal mushes ( $\phi \geq 0.5$ ) is ~3 wt.% (Figure 3B). In addition, elevated pressure (< 1.5 GPa) leads to a reduction in

~~$\eta_{melt}$  of about 2 orders of magnitude (e.g. Pistone et al., 2012), which may further promotes the efficiency of gas driven filter pressing. Overall, hydrous dacitic systems probably represent the optimal conditions of efficient gas driven filter pressing to promote melt segregation from shallow plutonic mushes (< 10 km). To assess gas driven filter pressing as a mechanism of melt extraction from shallow crystal mushes, the operating window controlled by melt permeability ( $\kappa$ ) and crystal mush expansion rates that permit inflation without fracture needs to be constrained. Extraction of silicic melts from a mush depends on  $\kappa$ , which is a function of melt fraction ( $\mu$ ) and crystal size ( $r$ ) (McKenzie, 1984):~~

$$\kappa = \frac{\mu^3 r^2}{A(1-\mu^2)} \quad (1)$$

~~can be used to assess the range of melt permeability ( $\kappa$ ) and crystal mush expansion rates that permit inflation without fracture, where  $\kappa$  is a function of melt fraction ( $\mu$ ) and crystal size ( $r$ ) (McKenzie, 1984; Jackson et al., 2003). For the crystal sizes ( $r = 68 \mu\text{m}$ ) and melt fractions in our experiments with  $0.25 < \mu < 0.4$  and  $r < 1 \text{ mm}$  (Jackson et al., 2003). Excluding systems with  $\phi \leq 0.5$  due to large gas permeability, the  $\mu$  considered ranges from 0.25 (minimum percolation threshold) to 0.4. If  $r = 68 \mu\text{m}$ ,  $\kappa$  ranges from  $2.7 \cdot 10^{-12} \text{ m}^2$  at ( $\mu = 0.25$ ) to  $7.05 \cdot 10^{-12} \text{ m}^2$  at ( $\mu = 0.4$ ) in our experiments.~~ The average velocity of melt percolation ( $v$ , positive upward within the mush) can then be estimated using Darcy's law:

$$v = \frac{\kappa}{\eta_{melt}} \times \frac{\nabla P}{\mu} \quad (2)$$

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~~where  $\nabla P$  is the gas pressure gradient.~~ To maintain a gas pressure gradient ( $\nabla P$ ) at a  
~~value necessary sufficient~~ to expel melt, ~~the region of magma undergoing gas~~  
~~exsolution must~~ inflation must be slower than ~~ly~~ relative to the rates at which it  
~~crystallises crystallisation and and exsolves~~ gas exsolution (Sisson and Bacon, 1999).  
~~From the bubble sizes~~ Following the approach of Anderson et al. (1984), and  
~~considering that bubbles~~ of 100-200  $\mu\text{m}$  diameter push driving melt ~~the melt~~ through  
20-80  $\mu\text{m}$  wide channels ~~within in~~ the crystal ~~framework mush~~ (Figure 1H) and a with  
~~a~~ mean gas expansion ( $\sim$  melt expulsion) rate of  $0.07 \mu\text{m}^3/\text{s}$  of during our experiments  
~~we find ( $\sim 45$  minutes), the resulting  $\nabla P$  is on in~~ the order of 0.1-1 MPa/m (after  
Anderson et al. 1984). Therefore, ~~in a  $\text{H}_2\text{O}$  (3 wt.%) and  $\text{SiO}_2$ -rich  $\eta_{\text{melt}} \sim 10^3 \text{ Pa}\cdot\text{s}$  at~~  
~~800  $^\circ\text{C}$ , (including the effect of pressure on  $\eta_{\text{melt}}$ ; Pistone et al., 2012) in the range~~  
 ~~$0.25 \leq \mu \leq 0.4$ , gas-driven filter pressing could therefore expel melt at  $v$  of between~~  
~~0.03-0.3 m/year at ( $\mu = 0.25$ ) and 0.05-0.5 m/year at ( $\mu = 0.4$ ).~~  
In natural silicic systems the mean size of the dominant phenocrysts (feldspar,  
hornblende, biotite, quartz) is  $\sim 3 \text{ mm}$  (Bachmann and Bergantz, 2004); so for  $\nabla P$   
 $\sim 0.1$ -1 PMa, expulsion velocities of 0.6-6 m/year ( $\mu = 0.25$ ) and 1.1-11 m/year ( $\mu =$   
0.4) are expected. This implies the segregation of crystal-poor melt bodies hundreds  
of meters thick can occur within a century, and could act as an efficient method of  
enhancing segregation compared to the ~~Compared to the longevities~~ of crystal  
mushes ( $10^4$ - $10^5$  years; Bachmann and Bergantz, 2004), provided gas-driven filter  
pressing could operate efficiently in shallow felsic mushes with  $\phi$  of 0.6-0.7 (Figure  
2) resulting in melt segregation and formation of overlying crystal-poor silicic melt  
caps. However, gas-driven filter pressing in a mush can only be effective where  
crystallisation and volatile exsolution occur sufficiently rapidly to establish maintain a

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~~large enough  $\nabla P$  without between gas bubble pressure and ambient pressure before the reaching the percolation threshold close packing of phases (~74 vol.%) impedes melt segregation. Despite the complexity of gas exsolution and crystallisation rates, bubble nucleation and growth kinetics, bulk viscosity changes, and build up of internal pressure (Costa et al., 2006), the results of this study serves as a general guide for the effectiveness of gas-driven filter pressing in particular situations. Compared to the longevities of crystal mushes ( $10^4$ – $10^5$  years; Bachmann and Bergantz, 2004), gas-driven filter pressing could operate efficiently in shallow felsic mushes with  $\phi$  of 0.6–0.7 (Figure 2) resulting in melt segregation and formation of overlying crystal-poor silicic melt caps. However, gas-driven filter pressing in a mush can only be effective where crystallisation and volatile exsolution occur sufficiently rapidly to establish a large enough  $\nabla P$  between gas bubble pressure and ambient pressure before the close packing of phases (~74 vol.%) impedes melt segregation.~~

~~—— In natural felsic plutons the mean size of the dominant phenocrysts (feldspar, hornblende, biotite, quartz) is about 3 mm (Bachmann and Bergantz, 2004); thus, at identical  $\nabla P$ , the  $v$  are expected to be 0.6–6 m/year at  $\mu = 0.25$  and 1.1–11 m/year at  $\mu = 0.4$ , with segregation of tens to hundreds meter-thick crystal-poor melts within a century. However, there is little evidence for the presence of large crystal-poor bodies in the present-day crust ( $10^2$ – $10^3$  km<sup>3</sup>; Bachmann and Bergantz, 2004). Thus, the expected volumes of silicic melt extracted from a mush via gas-driven filter pressing must be  $\ll 10^2$  km<sup>3</sup>, i.e. not detectable by high-resolution local seismic tomography (cell volume of 125 km<sup>3</sup>; e.g. Miller and Smith, 1999). If extracted from stagnant mushes, such small volumes of silicic melts may become highly hazardous due to their large volatile content (i.e. H<sub>2</sub>O dissolved in the melt + exsolved gas) and low  $\phi$ .~~

~~In conclusion, *in situ* observations of magmatic microstructural evolution have shown that gas-driven filter pressing can operate efficiently in shallow felsic crystal mushes with crystal volume fractions of 0.6–0.7 (Figure 2) provided crystallisation and volatile exsolution are rapid enough to establish a gas pressure gradient before the maximum packing fraction of bubbles and crystals is reached (~74 vol.%). Above this threshold, the crystal mush is likely to fracture, restricting melt segregation and hindering the generation of eruptible, crystal-poor magmas.~~ Gas-driven filter pressing is therefore a viable, but highly limited mechanism to rapidly extract large volumes of hazardous gas-rich crystal-poor magmas within the Earth's crust.

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## 410 FIGURE CAPTIONS

411 Figure 1. Synchrotron X-ray tomographic microscopy 3D renderings of two representative  
412 haplogranitic (H5, **A-D**) and dacitic samples (F, **E-H**) with different crystal ( $\Phi$ ) and bubble fractions  
413 ( $\beta$ ) at representative temperatures ( $T$ ) and experimental times ( $t$ , in minutes). Black objects = bubbles  
414 and fractures; dark grey field = silicic glass; light grey objects = corundum crystals in H5 glass and  
415 quartz in F glass. White and dark grey arrows indicate representative fractures and directions of melt  
416 expulsion during vesiculation respectively. During experiments gas exsolution mainly consists in: 1)  
417 bubble nucleation and growth (white circles), and 2) crystal clustering/compaction (white rectangles).  
418 Figure 2. Crystal fraction ( $\Phi$ ) vs. bubble fraction ( $\beta$ ) diagram reporting all experiments conducted in  
419 this study. Squares and circles indicate haplogranitic and dacitic samples respectively. Black and grey  
420 colours indicate ductile and brittle regime respectively. Dashed grey lines denote trends of constant  
421 melt fraction ( $\mu$ ). Grey field indicates impossible physical conditions. 2D reconstructed slices of  
422 representative samples display the increase of  $\beta$  with  $T$  and the increase of sample fracturing with  
423 increasing  $\Phi$ . Each side of the reconstructed slice is 5 mm. White areas in H5 samples are corundum  
424 crystals; dark grey areas in F samples are quartz crystals. In all samples black objects are gas bubbles,  
425 and light grey matrix is silicic glass. Values reported in each slice are  $T$  in °C.

426 Figure 3. **A**) KFT-measured amounts of H<sub>2</sub>O extracted from the melt of dacitic samples ( $\Phi = 0-0.8$ ) at  
427 different  $T$ . H<sub>2</sub>O uncertainties are  $\pm 0.07$  wt.% in the ductile (solid line) and  $\pm 0.14$  wt.% in the brittle  
428 regime (dashed line). **B**) Melt viscosity ( $\eta_{melt}$ ) as a function of extracted H<sub>2</sub>O, with  $\eta_{melt}$  estimated using  
429 the model of Giordano et al. (2008), taking into account the difference between the total H<sub>2</sub>O in the  
430 melt phase, measured in crystal-free F0 sample in **A**, and the extracted H<sub>2</sub>O at a specific  $T$ . At identical  
431 exsolution rates (i.e. heating rates applied during KFT measurements),  $\eta_{melt}$  is expected to evolve in the  
432 same manner in all dacitic samples; the  $\Phi$  increases the incapacity of H<sub>2</sub>O extraction from the sample  
433 (i.e. the higher  $\Phi$ , the lower the H<sub>2</sub>O extraction).  $\eta_{melt}$  uncertainties are:  $< 0.4$  log units at dissolved  
434 H<sub>2</sub>O contents  $< 2$  wt.%, and  $< 0.2$  log units at dissolved H<sub>2</sub>O contents  $> 2$  wt.%. Further  $\eta_{melt}$  deviations  
435 of 0.2 log units must be considered due to limited content of H<sub>2</sub>O ( $< 0.2$  wt.%) trapped in the F samples  
436 during vesiculation and not measured by KFT.

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